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Alternative Ozone Dose Metrics to Characterize Ozone Impact on Crop Yield Loss (Journal Version)

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Alternative Ozone Dose Metrics to Characterize Ozone Impact on Crop Yield Loss[1]

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ABSTRACT

Previous studies of the National Crop Loss Assessment Network (NCLAN) relating the impact of ozone (O_3) on agricultural crops have used the seasonal arithmetic average of O_3 for either a 7- or 12-h daily period as the measure of dose in the dose response relationships. This study investigated the use of alternative dose metics that gave differential weighting to hourly O_3 concentrations according to level of O_3, period of day, or total hourly solar radiation. Data were used from two NCLAN studies in which two different methods of O_3 addition were used for 7 h/d. In addition, one study included 12 h/d exposure for one method of O_3 addition. The residual sums of squares from fitting a common Weibull response model to each experiment were compared over the range of dose metrics. The results suggested that the dose metrics using equal weighting of peaks and valleys closely reflected plant reaction to O_3, but the fit of the dose-response models improved if relatively little weight was given to the final 5-h component (1700–2200 h EDT) of the 12-h exposure period. Weighting by total hourly solar radiation gave results very similar to the best obtained from differential peak-valley weighting and 7 h:5 h weighting.

Additional Index Words: Weibull response model, Soybean, *Glycine max.* (L.) Merr., Tobacco, *Nicotiana tobaccum* L., Power weighted mean.

The National Crop Loss Assessment Network (NCLAN) is composed of several research groups cooperating to assess the economic impact of ozone (O_3) on crop production. To obtain these economic assessments, dose response relationships between the yield of major agricultural crops and O_3 have been investigated. Experiments have been conducted since 1980 at four to six sites across the country; similar experimental designs and methods using open-top field chambers are followed at each site (Heck et al., 1984a, b). A data synthesis and analysis project was developed to archive the data from the NCLAN program and to allow a coordinated analysis of all data over all sites and years.

During the initial years of NCLAN, plants were exposed daily to several concentrations of O_3 over a 7-h period (1000–1700 h EDT). The daily 7-h mean averaged over the exposure period of the growing season was used as the O_3 exposure metric in the dose-response relationships. In the NCLAN experiments from 1980 to 1983, treatments with higher than ambient levels of O_3 were obtained by adding O_3 for 7 h/d at a constant rate to the variable concentrations in ambient air (Heagle et al., 1983; Kress and Miller, 1983; Heagle et al., 1986). (Additions were made to ambient levels of O_3 in order to retain the variable distribution of O_3 concentrations present under natural conditions.) More recently, O_3 has been added to ambient air in an amount *proportional* to the ambient air O_3 concentration and exposures have been for a 12-h daily time period (1000–2200 h EDT). The arithmetic average of daily O_3 concentrations ($\mu L\ L^{-1}$) over the 12-h exposure period over the exposure season is the dose metric currently being used for these dose response models.

The use of the seasonal average hourly O_3 concentration as the dose metric gives equal weight to each hourly concentration. Other research has suggested that plants incur greater damage from exposures to peak O_3 concentrations than is reflected in the simple average. Musselman et al. (1983), using 'Red Kidney' bean (*Phaseolus vulgaris* L. cv. Red Kidney), compared a 6-h constant O_3 exposure to a simulated ambient distribution of O_3, in which the concentration rose to a peak and then returned to zero in half-hour steps during the 6-h exposure period. The constant and simulated ambient exposures were defined so as to have the same mean dose. The simulated ambient exposure produced greater damage for most traits regardless of whether the plants received one, two, or three such exposures. Hogsett and Tingey (1985), using alfalfa (*Medicago sativa* L.), compared exposure treatments in which plants were exposed daily to either a constant daily profile or an episodic profile. At the high dose, plants receiving the episodic profile produced significantly less yield even though the average O_3 dose was slightly less. Other studies (see Lefohn and Runeckles, 1987, for a review) support the hypothesis that episodic exposures of O_3 are more damaging to plants than long-term, low concentration exposures.

These studies suggest that the dose metric should give greater relative weight to peaks than is given in the simple average. A dose metric that averages all exposures above a given threshold provides a two-step weighting, 0 or 1, depending on whether the dose is below or above the threshold. A continuous weighting function that reflects the relative damage caused by all dose levels would give a biologically more meaningful dose metric. Ideally, the dose metric would be defined so as to reflect the relative damage done by each increment of O_3. This might entail differential weighting of exposures with respect to time of day and stage of growth, assuming

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plants are not equally sensitive at all times of the day or at all stages of growth. A more complicated weighting function could allow for time intervals between episodes for plant recovery, if that is found to be important. Environmental factors, such as moisture stress, may also affect the relative amounts of damage done by different incremnets of O_3 exposure, and these could conceptually be included in the definition of a dose metric. It would appear more reasonable, however, to provide for the impact of environmental factors on the yield response to O_3 through the dose response function rather than through the definition of the dose metric. Lefohn and Runeckles (1987) gives more discussion on the relationship between the dose metric and O_3 standards.

The objective of this dose metrics study is to present the information contained in two NCLAN studies on alternative methods of averaging the O_3 exposure. Conceptually, a properly defined metric will reflect the effective dose (Cure et al., 1986) received by the plant and will give more consistent dose-response relationships over alternative exposure regimes. The alternative dose metrics considered in this study result from differential weighting of the hourly O_3 readings according to three criteria: (i) relative weighting of peak vs. nonpeak exposures, (ii) weighting with respect to time of day of exposure, and (iii) weighting with respect to total hourly solar radiation. The weighting by total hourly solar radiation is to demonstrate the use of a surrogate (admittedly crude) for plant activity (personal communication, R. P. Patterson) under the presumption that sensitivity to O_3 is related to plant activity. Weighting by solar radiation incorporates both time of day and time of growing season weighting.

MATERIALS AND METHODS

The two NCLAN experiments used in this report were conducted during the summers of 1982 and 1983 at the Southeast Regional NCLAN site, located 8 km south of Raleigh, NC (Heagle et al., 1986, 1987). Both studies included a comparison of the effects of the proportional and constant methods of O_3 addition.

In the 1982 study (Heagle et al., 1986), the impact of the constant and proportional 7 h/d O_3 additions on yield of soybean (*Glycine max* L. Merr. cv. Davis) were determined. Open top chambers were utilized, as described in previous NCLAN experiments, with O_3 dispensed from 1000–1700 h EDT from 20 July to 17 October (Heagle et al., 1979, 1986). There were eight chambered O_3 treatments in a randomized complete block design with two blocks. The treatments consisted of charcoal filtered air (CF), nonfiltered air (NF), and three treatments with O_3 added to NF chambers for each of the two methods of addition. The *constant* addition O_3 treatments consisted of 0.02, 0.04, and 0.06 μL/L of O_3 added to NF (C20, C40, and C60). The *proportional* addition O_3 treatments consisted of 1.3, 1.6, and 1.9 times the amount of O_3 present in NF air (P1.3, P1.6, and P1.9). The seasonal mean diurnal fluctuations in O_3 concentrations and the frequency distributions in O_3 concentrations are given in Heagle et al., 1986.

In the 1983 study (Heagle et al., 1987), the impacts of proportional 7 h/d and 12 h/d O_3 exposures and of constant and proportional 7 h/d O_3 addition were tested using flue-cured tobacco (*Nicotiana tabacum* L. cv McNair 944). There were 11 chambered treatments in a randomized complete block design with two blocks. Two of the chambered O_3 treatments were CF and NF. Three constant addition O_3 treatments used O_3 exposures of 0.015, 0.030, and 0.045 μL/L (C15, C30, and C45, respectively) added to NF chambers for 7 h/d (1000–1700 h EDT). The proportional O_3 treatments raised the O_3 to 1.3, 1.5, and 1.8 times (P1.3, P1.6, and P1.8, respectively) the level present in NF air for either 7 h/d (1000–1700 h EDT) or 12 h/d (1000–2200 h EDT). Exposures began on 2 June and continued through 22 August. The seasonal mean diurnal fluctuations in O_3 concentrations and the seasonal frequency distributions for the treatments in this study are discussed and shown in Heagle et al. (1987).

The differences in the exposure treatments of these two studies provides a basis for comparing alternative dose metrics. The proportional dispensing causes the frequency distribution of the hourly O_3 readings to be somewhat more variable than the constant addition (Heagle et al., 1986, 1987); hence, an opportunity to compare constant weighting with differential weighting of O_3 peaks. The additional 5 h of exposure in the 12 h/d exposure period allows comparisons of different relative weightings of the first 7 h and the last 5 h of exposure. It should be noted that the field studies used for this analysis were not designed specifically to test alternative dose metrics. All supplemental O_3 is imposed on top of ambient levels of O_3 and, consequently, the O_3 distributions for all treatments have the typical variable distributions of ambient O_3. The differences in the distributions of hourly O_3 concentrations between the proportional O_3 addition and the constant additions are relatively small compared to the differences one would obtain from experiments designed specifically to compare dose metrics (e.g., Musselman et al., 1983; Hogsett and Tingey, 1985). Consequently, the power in these studies is somewhat limited for this purpose.

Regression analyses of yield for each experiment (1982 and 1983) did not show any significant differences among the methods of O_3 addition ($\alpha = 0.05$). For the 1982 study, the dose metric used to compare constant and proportional methods was the 7 h/d seasonal mean. For the 1983 study, analyses were done using both the 7 h/d and 12 h/d seasonal means. Tests of homogeneity of yield response curves over the methods of O_3 addition were made by comparing a common Weibull response model to a model that allowed different responses for each dispensing method. Since the dispensing methods differed only for those treatments having supplemental O_3 applied, the response curves were forced to have a common linear response below the NF treatment, and then allowed to diverge into their separate Weibull curves above the NF treatment.

For purposes of testing the homogeneity of the dispensing methods, the common Weibull model is

$$Y_i = T(\beta_0 + \beta_1 O_{3i}) + (1 - T)\{\alpha \exp(-[O_{3i}/\omega]^{\lambda})\} + \epsilon_i \qquad [1]$$

where T is a dummy variable defined to be $T = 1$ if $O_3 \leq O_{3nf}$ and $T = 0$ otherwise (O_{3nf} is the dose of O_3 at the NF treatment), β_0 and β_1 are the intercept and slope coefficients, respectively, for the linear change in yield between the CF and NF treatments, and O_{3i} is the dose of O_3 for the ith treatment. The Weibull function parameters α, ω, and λ control the response to O_3 for dose levels above O_{3nf}. The parameter α is the theoretical yield at $O_3 = 0$, ω is the dose at which yield has been reduced to $\exp(-1)\,\alpha = 0.37\alpha$, and λ controls the shape of the curve; $\lambda = 1$ reflects an exponential decrease in yield, $\lambda \doteq 1.3$ reflects a nearly linear response in the low dose region (doses below ω), and increasingly larger values of λ reflect an increasing concentration of the effect of O_3 in the dose region near $O_3 = \omega$. Thus, the larger values of λ give a distinct plateau-type response before the effects of O_3 are exhibited. The linear and Weibull components of this segmented model are further restricted so that they meet at $O_3 = O_{3nf}$.

The more general model that allowed each dispensing method to have its own Weibull response was also a segmented linear-Weibull model as in (1) but with the Weibull component taking three forms depending on the method of dispensing. Restrictions were imposed so that all curves met at $O_3 = O_{3nf}$.

The tests of the dispensing methods did not show significant heterogeneity in either study using the 7- or 12-h average dose metric. (The tests of heterogeneity using polynomial models gave the same results). Subsequent analyses for comparing dose metrics used the conventional Weibull model (Rawlings and Cure, 1984).

$$Y_i = \alpha \exp[-(O_{3i}/\omega)^{\lambda}] + \epsilon_i \qquad [2]$$

where O_{3i} is replaced with the dose metric being considered.

In order to investigate alternative dose metrics, several power weighted dosages were calculated. A general weighted average of O_3 exposures can be written as

$$\Sigma\ (w_i x_i)/\Sigma w_i \qquad [3]$$

where the w_i are the weights and x_i are the hourly O_3 concentrations. If weighting is to be proportional to the concentration so that peaks get relatively more (or less) weight, the weights can be set equal to a power of the concentration, i.e., $w_i = x_i^p$. The power weighted mean, $\overline{W}_p$, is defined as

$$\overline{W}_p = \Sigma x_i^{p+1}/\Sigma x_i^p \qquad [4]$$

where choice of p determines the power weighting to be used, x_i is the hourly O_3 concentration, and i indexes the hourly observations. Summation is over all observations in the seasonal exposure period using either the 7 h/d or the 12 h/d exposure time periods. Ozone levels for treatments that received 7 h/d exposure returned to ambient levels for the remaining hours of the day. Thus, the 12 h power weighted mean for treatments receiving 7 h/d exposure averaged the ambient levels of O_3 for the final 5 h of the 12-h period.

The power weighted mean maintains the original units of measure and is transformed with respect to scale transformations the same as the original units. (For example, the transformation from ppm to ppb gives the same result whether the power weighted mean is computed before or after the transformation. However, the power weighted mean is not invariant to changes in the origin.) With $p = 0$, the denominator becomes the number of observations, and $\overline{W}_0$ is the seasonal arithmetic average of the O_3 exposures. Increasing positive values of p give increasing relative weight to peaks; increasing negative values of p give decreasing relative weight to peaks. The effect of power weighting can be illustrated by assuming the O_3 readings to be averaged are n equally spaced readings: a, $2a$, $3a$, ..., na. The arithmetic average ($p = 0$) gives $\overline{W}_0 = [(n + 1)/2]a$. The ratio of $\overline{W}_0$ to the peak O_3 reading in the series is 1/2 for large n. As the power weight increases to $p = 1$, 2, 3, and 4, the ratio of the power weighted mean to the peak reading increases to 2/3, 3/4, 4/5, and 5/6, respectively. In this illustration, the power weighted mean with $p = 4$, $\overline{W}_4$, is within 17% of the peak reading. Thus, for two sets of O_3 readings that have the same arithmetic average, the series with the greater dispersion (higher peaks) will have the larger power weighted mean when $p > 0$. For $p < 0$, the power weighted mean gives less relative weight to the peaks and the more uniform set of O_3 readings will give the larger power weighted mean.

For the experiments being compared, the proportional addition O_3 treatments show greater dispersion in O_3 levels than the constant addition O_3 treatments. Thus, for proportional addition and constant addition treatments having the same arithmetic mean ($p = 0$), the power weighted means for the proportional addition treatment will become increasingly larger than the corresponding constant addition treatment power weighted means as p increases. This trend is seen in Table 1 by comparing the 12-h power weighted means for C15 and P1.3 treatments, C30 and P1.5 treatments, and C45 and P1.8 treatments using the 7-h exposure period.

Table 1. Twelve-hour O_3 dose metrics (μL/L) for tobacco study, 1983, using power weighting of dose with p ranging from $p = -0.5$ to $p = 4$† and weighting proportional to total solar radiation.

Treatment design‡	$p = -0.5$	$p = 0$	$p = 1$	$p = 4$	Total solar radiation
CF	0.0231	0.0276	0.0350	0.0467	0.0317
NF	0.0445	0.0520	0.0614	0.0720	0.0596
C15 (7)	0.0538	0.0651	0.0779	0.0931	0.0796
P1.3 (7)	0.0643	0.0676	0.0850	0.1082	0.0848
P1.3 (12)	0.0714	0.0835	0.0984	0.1164	0.0944
C30 (7)	0.0584	0.0723	0.0887	0.1073	0.0912
P1.5 (7)	0.0591	0.0762	0.1006	0.1325	0.0988
P1.5 (12)	0.0802	0.0963	0.1151	0.1360	0.1087
C45 (7)	0.0634	0.0812	0.1025	0.1240	0.1046
P1.8 (7)	0.0643	0.0864	0.1198	0.1593	0.1153
P1.8 (12)	0.0930	0.1136	0.1371	0.1625	0.1280
AA	0.0574	0.0630	0.0706	0.0813	0.0707

† Power weighted means were also computed for $p = 2$, and $p = 3$. The means for all treatments followed the same pattern as the p values listed and hence are not presented.

‡ CF = charcoal-filtered air, NF = nonfiltered air, AA = ambient air. C15, C30, and C45 = constant additions of O_3 at 0.015, 0.030, and 0.045 mL/L, respectively; P1.3, P1.5, and P1.8 = proportional addition of O_3 at a rate of 1.3, 1.5, and 1.8 times the current ambient air reading, respectively. The number in parentheses identifies the daily exposure period: (7) = 1000–1700 h EDT, (12) = 1000–2200 h EDT).

A second dose metric was defined that used hourly total solar radiation (W/m^2) as the weighting function, w_i, in the O_3 averaging (Eq. [3]). Solar radiation was chosen as an environmental variable available in meterological records that would approximately reflect plant activity at the time of exposure. The hypothesis is that the *effective* dose to the plant is proportional to plant activity at the time of exposure. It is recognized that solar radiation, like any other single meterological or environmental variable, is only an approximate predictor of plant activity. Drought stress, for example, might cause plant activity to be severely restricted at a time of high solar radiation. The hourly total solar radiation was recorded at the meterological station at the field site. The solar radiation weighted O_3 means were computed for the 7-h averaging period for the 1982 study and for both the 7- and 12-h averaging periods for the 1983 study. The average hourly weighting provided by the "radiation" weighting is reflected in the hourly mean total radiation curves for the dispensing season (Fig. 1). The 12-h "radiation" means for the 1983 study are shown in Table 1. The "radiation" means in this experiment fall slightly above the $\overline{W}_1$ means for the constant addition treatments, slightly below $\overline{W}_1$ for the proportional 7-h treatments, and near the $\overline{W}_{0.5}$ means (not shown) for the proportional 12-h treatments.

The third dose weighting to be compared in this study allowed different relative weights for the 7-h (1000–1700 h EDT) and the 5-h (1700–2200 h EDT) daily time periods in addition to power weighting of the hourly readings separately within the 7-h and the 5-h periods. Only the 1983 experiment provided a basis for this comparison. For this purpose, the power weighted means were computed separately for the 7- and 5-h daily time periods and than averaged with appropriate weights to obtain the 12-h joint power and time-of-day weighted average. The 7- and 5-h power weighted means are denoted by $\overline{W}_{7p}$ and $\overline{W}_{5p}$, respectively, where summation in each power weighted mean (Eq. [4]) is over the hourly O_3 readings for the indicated

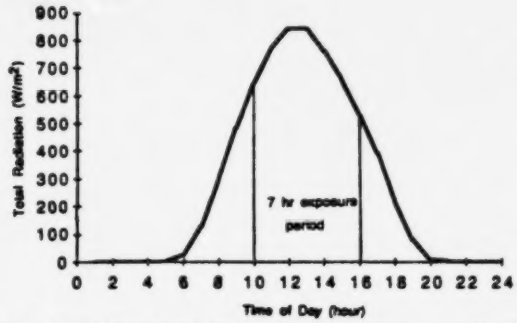

Fig. 1. Mean hourly total solar radiation averaged over the 1982 dispensing season.

daily time interval for the entire exposure season. If γ is the weight given to the 7-h period and $(1 - \gamma)$ is the weight given the 5-h period, then the power, time-of-day weighted mean is

$$\overline{W}_{\gamma,p} = \gamma\overline{W}_{7p} + (1 - \gamma)\overline{W}_{5p} \quad [5]$$

The best choice of γ for the time-of-day weighting was investigated two ways. First, $\overline{W}_{\gamma,p}$ were computed for several choices for γ corresponding to relative weights of γ to $(1 - \gamma)$ of 7:5, 8:4, 9:3, 10:2, 11:1, and 12:0. (The 12:0 relative weighting, $\gamma = 1$, gives the 7-h power weighted O_3 dose metric. However, the 7:5 relative weighting, $\gamma = 7/12$, will not produce the 12-h power weighted O_3 dose metric.) The best choice of γ was determined by the dose metric that gave the smallest residual sum of squares for the fitted model. The second method of determining the 7 h:5 h relative weighting incorporated γ as a parameter in the model, which was then estimated by least squares. For comparison with the Weibull model, the 7 h:5 h weighting for a linear response model was also estimated.

RESULTS

As p increases in the power weighted mean dose metric, relatively greater weight is placed on the higher peaks of O_3 exposure. For similar mean O_3 levels among the constant and proportional methods of addition, increasing p results in higher O_3 means for both methods. However, since the proportional method of dispensing creates greater dispersion, larger values of p produce relatively higher seasonal O_3 power weighted means for proportional than for constant addition. Table 1 shows this using the 12-h power weighted mean. For example, each pair of the 7 h/d treatments (C15 vs. P1.3, C30 vs. P1.5, C45 vs. P1.8) shows similar dose levels for the unweighted dose metric ($p = 0$), but the proportional treatment dose metric becomes increasingly larger than the constant treatment O_3 dose for larger powers (p).

Weighting of O_3 concentrations by total hourly solar radiation provides differential weighting during the day, and to some extent, over the growing season. The relative weightings given to the hourly O_3 values are reflected in the seasonal average hourly total solar radiation curve (Fig. 1). Maximum weighting is given to the 1100–1400 h period with total solar radiation dropping rapidly after 1400 h. "Radiation" weighting gives relatively little weight to the final 5 h (almost zero weight to the final 3 h) of the 12-h exposure period (1700–2200 h). Since the total solar radiation curve (Fig. 1) closely parallels the average diurnal O_3 concentration curve, the radiation weighted metric is highly correlated with the power weighted dose metrics. For example, in the 1983 study, the correlations over the treatments of the radiation weighted metric with the power weighted metric is 0.915, 0.970, 0.993, and 0.979 for $p = -0.5$, 0, 1, and 4, respectively. Likewise, the correlations among the power weighted means are high ranging from 0.858 to 0.985.

Table 2. Residual sums of squares from Weibull models for the 1982 (soybean) and 1983 (tobacco) studies using 7- and 12-h (1983 only) power weighted means and "radiation" weighted means. The power weights ranged from $p = 0$ to $p = 4$; p = Rad is weighting proportional to total hourly solar radiation.

	1982	1983	
p	7-h mean	7-h mean	12-h mean
0	18 498	5 154	7 852
1	16 378	6 146	6 329
2	18 872	6 811	6 696
3	21 161	7 250	7 149
4	26 879	7 577	7 452
Rad	16 776	5 516	5 378

For the 1982 study, fitting the common Weibull response over all dispensing methods gave the smallest residual sum of squares (of those studied) when the 7 h power weighted dose metric with $p = 1$, $\overline{W}_1$, was used (Table 2). The residual sum of squares from using the "radiation" dose metric was close to this minimum. This residual sum of squares is not significantly smaller than that for $p = 0$, equal weighting. When each dispensing method was allowed to have its own response curve, the curves were not significantly heterogeneous for the "radiation" weighted dose metric or for the power weighted dose metric as long as $p < 2$. But with $p > 2$, the response curves for the different dispensing methods became significantly heterogeneous.

For the 1983 study, both the 7- and 12-h averaging periods were used. Of the values of p shown in Table 2, the power weighted mean with $p = 0$, $\overline{W}_0$, for the 7-h averaging period and $p = 1$, $\overline{W}_1$, for the 12-h averaging period gave the minimum residual sums of squares. For the 7-h averaging period, the residual sum of squares using the "radiation" dose metric was only slightly higher than that for $\overline{W}_0$. (Results in Table 3 suggest that the minimum for the 7-h averaging period is attained near $p = -0.5$.) For the 12-h averaging period, the "radiation" dose metric gave an appreciably *smaller* residual sum of squares than did $\overline{W}_1$. There was no significant heterogeneity among the response curves for the different dispensing methods using the power weighted dose metrics with $p < 2$ when the 12-h averaging period was used. However, the response curves became significantly different for power weighted dose metrics with $p > 2$.

The results from the joint consideration of 7 h:5 h weighting and power weighting of O_3 for the 1983 experiment are given in Table 3 and Fig. 2. (Note that the line from Table 3 for $\gamma = 12/12$ gives the 7-h power weighted results in Table 2.) The minimum residual sum of squares obtained for the Weibull model for each value of p is underscored. For all choices of p, the optimum 7 h:5 h

Table 3. Residual sums of squares from Weibull models for the 1983 tobacco study using power and time-of-day weighted O_3 means. The nonlinear least squares estimate of time-of-day weighting, γ, is included for each p.

7 h:5 h Weighting (γ)†	Power weight (p)					
	−1	−0.5	0	0.5	1	2
7/12	6561	7172	7837	8169	8364	8565
8/12	5535	5975	6656	7059	7322	7644
9/12	5098	5186	5799	6250	6573	7008
10/12	5074	4775	5272	5757	6131	6663
11/12	5311	4696	5069	5579	5992	6598
12/12‡	5697	4881	5154	5685	6146	6811
Nonlinear	9.55	10.76	11.18	11.10	10.98	10.74
est. of γ	12	12	12	12	12	12

† γ is the relative weight given the 7-h (1000–1700 h EDT) daily time periods. The weight given the 5-h (1700–2220 h EDT) is $1 - \gamma$. The bold number is the minimum residual sum of squares in the table; the underscored number in each column is the minimum for that value of p.
‡ The weight 12/12, no weight given to the 5-h mean, results in the 7-h power weighted mean. These results differ slightly from those in Table 2 due to slight differences in convergence of the nonlinear models.

Table 4. Least squares estimation of 7 h:5 h weighting, γ, for the 1983 tobacco experiment from both the linear and Weibull models.

	Linear			Weibull		
	$p = -0.5$	$p = 0$	$p = 1$	$p = -0.5$	$p = 0$	$p = 1$
β_1†	−1528	−1393	−1186	–	–	–
β_2	−201	−119	−111	–	–	–
RSS‡	6115	5832	6251	4688	5064	5992
Estimate of γ§	10.60 / 12	11.06 / 12	10.97 / 12	10.76 / 12	11.18 / 12	10.98 / 12

† The β represent the regression parameters estimated from the model: $Y = \beta_0 + \beta_1(W_{7p}) + \beta_2(W_{5p}) + \epsilon$.
‡ RSS is the residual sum of squares.
§ The estimates of the relative weight for the 7-h exposure period. The relative weight for the 7-h period is computed as $12\beta_1/(\beta_1 + \beta_2)$. This is expressed as a multiple of 12 for comparison with the weights in Table 3.

weighting gave considerably more weight, $\gamma = 10/12$ or $\gamma = 11/12$, to the 7-h period than would a simple weighting based on duration of each period, $\gamma = 7/12$. For each choice of γ, the power weighting that gave the minimum sum of squares was either $p = -1$ or $p = -0.5$. The overall minimum residual sum of squares of all cases studied (4696) was obtained with $p = -0.5$ and $\gamma = 11/12$. This residual sum of squares is appreciably smaller than the minimum obtained using the 12-h power weighted means (6329, Table 2) and somewhat smaller than that obtained using the "radiation" mean (5378). It is only slightly smaller than that obtained using $\gamma = 11/12$ weighting of the arithmetic ($p = 0$) O_3 means (5069). The limits on an approximate 90% confidence interval estimate of p, conditional on $\gamma = 11/12$, include all values of p in Table 3 except $p = 2$. Similarly, an approximate 90% confidence interval estimate of γ, given $p = -0.5$, includes all values of γ in Table 3 except $\gamma = 7/12$.

The nonlinear least squares estimates of γ, using the Weibull model, are very close to 11/12 for all power weighted means investigated except for $p = -1$, where $\hat{\gamma} = 9.55/12$ (last line of Table 3). The estimates of γ were also obtained using a linear response model with two O_3 dose metric terms; the power-weighted O_3 dose of the first 7 h/d exposure period, $\overline{W}_{7p}$, and another for the final 5 h/d exposure period, $\overline{W}_{5p}$. The least squares estimates of γ for these linear models were obtained by rescaling the regression coefficients to 12 (Table 4). The estimates obtained are also very close to 11/12 for all values of p investigated.

In summary, the 1982 7-h power weighted mean and the 1983 12-h power weighted mean results suggest that high dose exposures should be weighted more heavily than simple averaging. However, the 1983 7-h power weighting and the joint consideration of power weighting and 7 h:5 h time of day weighting in the 1983 study support the conventional averaging and may even be suggestive of giving less weight to the peak values than does simple averaging. The 7 h:5 h weighting consistently indicated that considerably less weight be given the last 5 h of the 12-h exposure period. The radiation weighted dose metric consistently gave residual sums of squares near the minimum.

DISCUSSION

Changes in the fit of the dose response models (as measured by the residual sums of squares) for different O_3 dose metrics are used to investigate how hourly O_3 readings might best be averaged to reflect the effective dose being experienced by the plants. Different methods of O_3 dispensing (constant vs. proportional) and different dispensing time periods (7 h vs. 12 h) caused differences in frequency distributions of the hourly O_3 concentrations. These differences provided an opportunity for testing different dose metrics based on the differential weighting of peaks and valleys of O_3 exposure and on time-of-day weighting. In all cases, the frequency distributions of O_3 concentrations were highly variable, showing the typical diurnal pattern and varying peaks of exposure from day-to-day characteristic of ambient O_3 distributions. These "within study" differences in the frequency distributions caused by the different methods of dispensing are small compared to those that would be realized from, for example, a constant O_3 exposure vs.

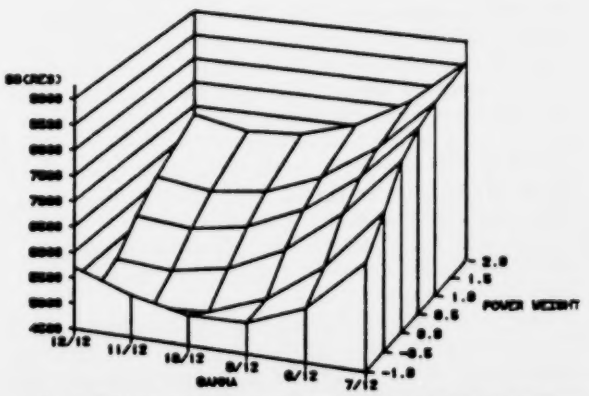

Fig. 2. Residual sums of squares surface from fitting a common Weibull model for combinations of power weighting, p, and time-of-day weighting, γ. The minimum point on the surface gives the least squares estimate of p and γ.

an episodic exposure, or possibly from comparing O_3 distributions over sites and years. Consequently, the power in these studies to distinguish among dose metrics is less than desired. (The wide confidence intervals on p and $\hat{\gamma}$ reflect the relatively low power of these studies.) While the power may be less than desired, the O_3 frequency distributions in these studies do represent the types of distributions expected under ambient conditions. Higher power for distinguishing among alternative dose metrics would be realized from experiments specifically designed to give greater differences in exposure regimes for whatever aspects are of interest.

A second result of the experiments not being designed specifically to compare dose metrics is that the dose metrics for the three weightings being compared, peaks vs. valleys, time of day, and radiation are highly correlated. Consequently, the effects of the three weightings cannot be clearly separated. The diurnal total hourly radiation curve is very similar in shape to the diurnal average hourly O_3 concentration curve so that weighting by one is similar to weighting by the other. Likewise, the 7 h:5 h weighting tends to mimic the radiation and dose weighting since the 7-h period correspoonds (roughly) to the peak period of both the radiation and the O_3 diurnal curves.

The power weighted dose metrics, $\overline{W}_p$, failed to provide a consistent indication that peak O_3 levels should be given greater weight than that provided by the simple arithmetic average, $p = 0$, ($\overline{W}_0$). The 1982 study gave the best fit to a common Weibull model when the dose metric $\overline{W}_1$ was used. When only power weighting was used in the 1983 study, the 7-h averaging period gave the minimum residual sum of squares with $p = -0.5$ (see Table 3 for $\gamma = 12/12$). The 12-h averaging period gave a minimum residual sum of squares with $p = 1$, but this minimum was much larger than the minimum for the 7-h averaging period. Further, the optimal power weighting changed to $p = -0.5$ when both power weighting and time-of-day weighting were used on the 1983 study. The negative values of p suggest that less weight be given to the peak O_3 occurrences than that given in the arithmetic average. The NCLAN dose response studies to date have used the arithmetic average of the hourly O_3 readings during the exposure period, $\overline{W}_0$, as the dose metric. These preliminary studies with power weighted averaging suggest that the NCLAN dose metric is a reasonable dose metric insofar as relative weighting of peaks and valleys of the O_3 occurrences is concerned. On the other hand, since none of the results suggested power weighting greater than $p = 1$, the results are consistent in indicating that the effective dose metric is *not* well represented by only the extreme exposures.

The results indicate that O_3 exposure during the final 5 h period (1700–2200 h EDT) has some effect on plant response but that this period is much less important than the 7-h period in the middle of the day (1000–1700 h EDT). The estimates of γ from the joint consideration of time-of-day and power weighting consistently gave little weight to the 5-h period (Tables 3 and 4). The "radiation" weighted dose metric, which gave the minimum residual sum of squares for the 12-h averaging period in the 1983 study and near minimum residual sums of squares for the 7-h averaging period in 1982 and 1983 (Table 2), gives relatively little weight to the first 2 h of the 5-h period and almost zero weight to the final 3 h (Fig. 1). The similarity of the average diurnal curves for total hourly solar radiation and hourly O_3 concentrations and the similarity of the "radiation" weighted metric to the power weighted metric with p in the region of 0.5 to 1.0 (Table 1) suggest that the power weighted metric is providing similarly low relative weighting for the final 5 h.

When the power weighted dose metric is computed over the entire 12-h exposure period there is the suggestion in the 1983 data that peak exposures are having a greater effect than is reflected in the simple average dose (Table 2). However, when the power weighted metrics are computed separately within the 7- and 5-h components of the 12-h exposure period and then combined in a weighted average, the estimated optimal power weighting is less than zero ($p < 0$) regardless of the 7 h:5 h weighting used (Table 3). Since the 7 h:5 h split approximately corresponds to the major shift from high midday O_3 levels to the lower evening O_3 levels, the hourly O_3 frequency distributions within each of these time intervals will be less variable than the distribution over the entire 12-h period. These results ($p < 0$) suggest that, within the restricted frequency distribution of each time interval, the differential impact of peaks and valleys of O_3 exposure is unimportant, or at least not detectable in these data. The fact that the 12-h power weighted mean in the 1983 data gave greater weight to the peaks ($p = 1$, Table 2), whereas the separate 7- and 5-h power weighting gave less weight to the peaks ($p < 0$) would seem to suggest that the impetus for the peak weighting in the 12-h metric stems from the difference between the 7- and 5-h time periods. In addition to the change in distributions of the O_3 concentrations, there is also a major change in average plant activity between the 7-h period (1000–1700 h DT) and the 5-h period (1700–2200 h DT). Thus, the apparent advantage of weighting the peaks more heavily ($p = 1$) in the 12-h 1983 metric might be attributable to either greater relative impact of peak episodes of O_3 or to changes in plant sensitivity associated with plant activity (as measured here by solar radiation).

The solar radiation weighted dose metric is an initial attempt to weight O_3 exposure by the relative plant activity at the time of exposure. Ozone exposure occurring on cloudy days, late in the day, or late in the growing season will tend to be weighted less heavily. The consistency with which the "radiation" weighting gave residual sums of squares near the minimum suggests that level of plant activity should be given more consideration in the definition of dose metrics. Further research into dose metrics that weight O_3 exposures by more appropriate measures of plant activity at the time of exposure may be worthwhile.

These analyses used the results from two studies (soybean and tobacco) conducted at Raleigh, NC. While the results were reasonably consistent for both studies, it is clear that general inferences to other sites or other years

are not warranted, and no such inferences are intended. Many environmental factors differ between locations and years, which may influence how dispensed O_3 interacts with the plant. The intent of this report is to provide additional information on factors that might affect the definition of dose metrics and, hopefully, in the process stimulate more research directly aimed at the definition of effective dose.

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